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PRESSURE MEASUREMENT BY CRUSHER GAUGES - NATO APPROVAL TESTS FOR CRUSHER GAUGES

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PUBLICATION

NATO ARMY ARMAMENTS GROUP

SURFACE-TO-SURFACE ARTILLERY PANEL

PRESSURE MEASUREMENT BY CRUSHER GAUGES

NATO APPROVAL TESTS FOR CRUSHER GAUGES

09/91

NORTH ATLANTIC TREATY ORGANIZATION

MILITARY AGENCY FOR STANDARDIZATION (MAS)

NATO LETTER OF PROMULGATION

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2. AEP-23 is effective upon receipt.

3. AEP-23 contains only practical information. As any corrections that the nations concerned may make to it are not subject to ratification they will be promulgated upon receipt.

E. Stai

E. STAI
Major-General, NOAF
Chairman, MAS

RECORD OF CHANGES

Change Date	Date Entered	Effective Date	By Whom Entered

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PART I

NATO APPROVED CRUSHER GAUGES

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CHAPTER 1

GENERAL

A NATO approved crusher gauge is defined as the combination of gauge components and a crusher, for neither the gauge components nor the crusher can be used alone.

NATO approved crusher gauges are used to measure the maximum pressure developed in the chamber of a gun during the firing of a round. Crusher gauges are normally preferred to electrical gauges because crusher gauges are simpler to use. The crusher housed within the gauge body is plastically deformed by a piston subjected to the transient gas pressure. After firing, the remaining length of the crusher is measured and from this the applied pressure can be deduced.

A list of NATO approved crusher gauges is at Annex and detailed figures for each gauge, together with resulting limitations, are at Appendices 1 to 5.

ANNEX I - NATO APPROVED CRUSHER GAUGES

COUNTRY	CRUSHER GAUGE	CRUSHER	CRUSHER DIMENSIONS	TYPE	RANGE OF USE
United States	T 19	Sphere - Lot N°1-85	4.763	LP	see Appendix 1
	M 11	"	"	HP	"
	M 12	"	"	HP	"
United Kingdom	MK8	Sphere - Lot N°8	4.763	LP	see Appendix 2
	MK9	"	"	HP	"
Spain	MT 26 BP	Cylinder-Lot N° 05-90-C1-MT26	5x7	LP	see Appendix 3
	MT 26 AP	"		HP	"
Germany/ Netherlands	31/701	Sphere - Lot N°90-91-01	6	LP	see Appendix 4
	38/3.91	"	"	HP	"
France	FAN	Cylinder - Lot N°1-90	3x4.9	LP and HP	see Appendix 5

Note: This Annex and the associated appendices are based on the results of the 1990 NATO comparative firings in Bourges.

APPENDIX 1 to
ANNEX to
CHAPTER 1 of
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RANGES AND LIMITS - US

STANDARD ACCEPTANCE CRITERIA

Indicators of precision (F) and accuracy of the mean (J) of the gauge.

F/J

Pressure (bars)	-40 to -30	-30 to +63
4000 – 6500	(2) 2/4	2/2
500 – 4000	2/2	1/2

Temperature (degrees Celsius)

GAUGE: T 19

Indicators of precision of the gauge

F(%)

Pressure (bars)	-40	-33	-13	21	52	63
2300	98	61	1.28	38	76	17
2000	65	40	83	64	50	78
1700	84	49	38	51	33	59
1400	70	65	66	46	68	54
1100	87	91	49	85	59	66
800	1.02	95	1.08	59	98	60
500	1.40	1.22	1.55	77	1.08	77

Temperature (degrees Celsius)

Indicators of accuracy of the mean of the gauge J (%)

Pressure (bars)	-40	-33	-13	21	52	63
2300	1.03	86	1.26	43	73	33
2000	69	76	1.34	61	56	82
1700	93	56	46	72	57	59
1400	69	78	81	50	1.16	68
1100	1.69	1.27	73	1.17	82	69
800	1.29	1.51	1.69	66	93	62
500	2.23	1.51	1.52	66	1.17	70

Temperature (degrees Celsius)

GAUGES: M11 (positive temperatures) and M12 (negative temperatures)

Indicators of precision of the gauge

F(%)

Pressure (bars)	-40	-33	-13	21	52	63
6500	1.48	1.01	39	1.09	57	76
6000	1.02	80	40	52	69	85
5200	1.04	49	58	38	55	45
4400	1.03	58	73	47	58	58
3700	84	65	54	48	51	51
2900	48	45	51	65	44	64
2200	82	83	62	44	50	65
1700	87	73	47	79	72	32

Temperature (degrees Celsius)

Indicators of accuracy of the mean of the gauge J(%)

Pressure (bars)	-40	-33	-13	21	52	63
6500	2.99	1.53	50	4.21	1.96	96
6000	2.96	1.03	1.38	1.94	2.04	1.75
5200	1.17	1.41	1.13	54	87	1.50
4400	1.09	1.82	1.22	64	89	82
3700	86	83	97	57	51	57
2900	65	88	1.21	1.08	41	70
2200	1.27	1.03	1.17	1.00	76	1.15
1700	1.31	1.48	83	1.05	1.24	66

Temperature (degrees Celsius)

Notes: (1) Values underlined are those that exceed the standard criteria.
(2) Panel IV (SP/2) may authorise 4% for F for pressures above 4000 bars at temperatures below -30C°.

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RANGES AND LIMITS - UK

STANDARD ACCEPTANCE CRITERIA

Indicators of precision (F) and accuracy of the mean (J) of the gauge.

F/J

Pressure (bars)	-40 to -30	-30 to +63
6500–4000	(2) 2/4	2/2
4000–500	2/2	1/2

Temperature (degrees Celsius)

GAUGE: MK 8

Indicators of precision of the gauge F(%)

Pressure (bars)	-40	-33	-13	21	52	63
2300	3.05	2.37	1.03	52	77	1.02
2000	2.48	2.18	70	83	88	58
1700	1.67	1.07	63	58	71	61
1400	1.37	63	51	56	36	42
1100	69	59	53	50	47	45
800	60	62	60	62	47	63
500	68	61	70	49	67	45

Temperature (degrees Celsius)

Indicators of accuracy of the mean of the gauge. J(%)

Pressure (bars)	-40	-33	-13	21	52	63
2300	6.10	2.78	2.08	1.23	2.12	1.79
2000	3.48	2.91	1.95	1.05	95	98
1700	2.36	1.12	1.61	61	76	95
1400	1.79	1.44	1.48	63	1.18	1.11
1100	1.38	1.17	1.11	91	47	57
800	96	2.61	70	1.31	1.04	1.09
500	2.77	96	89	95	1.04	73

Temperature (degree Celsius)

GAUGES: MK 9

Indicators of precision of the gauge F(%)

Pressure (bars)	-33	-13	21	52	63
6500	2.10	1.44	70	50	56
6000	89	1.03	35	39	58
5200	1.00	81	58	60	56
4400	71	35	62	45	54
3700	60	67	24	51	42
2900	50	83	60	59	66
2200	61	58	52	41	82
1700	56	70	49	51	52

Temperature (degrees Celsius)

Indicators of accuracy of the mean of the gauge. J(%)

Pressure (bars)	-33	-13	21	52	63
6500	6.73	2.25	79	1.94	1.02
6000	5.18	3.46	54	87	65
5200	2.60	4.13	63	76	1.33
4400	1.25	2.50	76	47	1.37
3700	96	1.98	46	55	97
2900	1.50	1.43	71	62	72
2200	1.65	1.70	1.44	1.04	1.00
1700	1.71	1.20	98	73	98

Temperature (degrees Celsius)

Notes:
(1) Values underlined are those that exceed the standard criteria.
(2) Panel IV (SP/2) may authorise 4% for F for pressures above 4000 bars at temperatures below -30C°.

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RANGES AND LIMITS - SP

STANDARD ACCEPTANCE CRITERIA

Indicators of precision (F) and accuracy of the mean (J) of the gauge.

F/J

Pressure (bars)	-40 to -30	-30 to +63
above 4000	(2) 2/4	2/2
500 to 4000	2/2	1/2

Temperature (degrees Celsius)

GAUGE: MT 26 - BP

Indicators of precision of the gauge F(%)

Pressure (bars)	-40	-33	-13	21	52	63
2300	50	35	65	32	25	26
2000	74	62	1.06	37	48	43
1700	71	55	55	44	48	39
1400	1.02	55	78	47	55	55
1100	1.08	57	1.16	68	84	37
800	1.21	1.11	1.12	79	86	60

Temperature (degrees Celsius)

Indicators of accuracy of the mean of the gauge. J(%)

Pressure (bars)	-40	-33	-13	21	52	63
2300	45	56	1.29	77	1.04	88
2000	1.43	83	2.67	82	82	1.15
1700	3.11	65	1.82	59	52	73
1400	1.90	92	2.19	46	1.03	76
1100	1.37	64	3.50	85	1.40	47
800	1.75	1.24	3.72	98	90	80

Temperature (degree Celsius)

GAUGES: MT 26 -AP

Indicators of precision of the gauge F(%)

Pressure (bars)	-40	-33	-13	21	52	63
5200		52	24	59	26	34
4400	86	56	36	30	33	26
3700	51	40	40	40	27	36
2900	70	61	37	38	31	34
2200	78	61	32	45	51	22
1700	1.20	68	21	57	51	35

Temperature (degrees Celsius)

Indicators of accuracy of the mean of the gauge. J(%)

Pressure (bars)	-40	-33	-13	21	52	63
5200		95	40	67	1.26	88
4400	1.66	1.03	86	38	79	75
3700	1.39	67	79	39	42	78
2900	2.59	1.45	1.77	52	62	63
2200	5.04	1.30	1.48	63	1.05	91
1700	5.55	86	81	1.01	85	65

Temperature (degrees Celsius)

Notes: (1) Values underlined are those that exceed the standard criteria.
(2) Panel IV (SP/2) may authorise 4% for F for pressures above 4000 bars at temperatures below -30C°.

RANGES AND LIMITS - GE/NL

STANDARD ACCEPTANCE CRITERIA

Indicators of precision (F) and accuracy of the mean (J) of the gauge.

F/J

Pressure (bars)	-40 to -30	-30 to +63
4000 – 6500	(2) 2/4	2/2
500 – 4000	2/2	1/2

Temperature (degrees Celsius)

GAUGE: 31/701

Indicators of precision of the gauge F(%)

Pressure (bars)	-40	-33	-13	21	52	63
2300	44	61	50	32	27	66
2000	64	41	38	50	49	30
1700	63	59	40	47	48	52
1400	43	49	42	28	23	39
1100	31	54	60	55	87	54
800	67	55	<u>1.01</u>	46	80	43
500	74	75	1.00	53	86	72

Temperature (degrees Celsius)

Indicators of accuracy of the mean of the gauge. J(%)

Pressure (bars)	-40	-33	-13	21	52	63
2300	39	65	55	45	32	64
2000	78	45	49	85	91	38
1700	79	65	49	85	58	52
1400	45	52	44	75	29	94
1100	82	1.07	59	60	1.05	67
800	1.09	1.42	97	55	1.67	72
500	1.47	<u>2.14</u>	96	1.06	1.39	1.20

Temperature (degree Celsius)

GAUGES: 38/3.91

Indicators of precision of the gauge F(%)

Pressure (bars)	-40	-33	-13	21	52	63
6500		79	65	55	24	48
6000		55	46	58	39	37
5200	72	50	47	41	53	37
4400	47	70	70	48	62	53
3700	74	68	72	54	47	75
2900	61	33	47	64	57	53
2200	76	68	74	70	57	54
1700	53	61	91	52	47	81

Temperature (degrees Celsius)

Indicators of accuracy of the mean of the gauge. J(%)

Pressure (bars)	-40	-33	-13	21	52	63
6500		1.69	1.36	<u>2.41</u>	86	92
6000		61	1.77	1.20	55	49
5200	1.59	1.16	1.68	1.00	85	1.34
4400	1.46	2.08	1.41	57	74	89
3700	1.76	98	85	52	46	77
2900	69	39	62	74	60	57
2200	99	98	74	65	65	84
1700	76	75	1.93	72	77	87

Temperature (degrees Celsius)

Notes:
(1) Values underlined are those that exceed the standard criteria.
(2) Panel IV (SP/2) may authorise 4% for F for pressures above 4000 bars at temperatures below -30C°.

RANGES AND LIMITS - FR

STANDARD ACCEPTANCE CRITERIA
Indicators of precesion (F) and accuracy of the mean (J) of the gauge.
F/J

Pressure (bars)	-40 to -30	-30 to +63
6500–4000	(2) 2/4	2/2
4000–500	2/2	1/2

Temperature (degrees Celsius)

GAUGE: FAN
Indicators of precision of the gauge
F(%)

Pressure (bars)	-40	-33	-13	21	52	63
2300	45	59	60	57	52	58
2000	74	34	70	54	66	58
1700	75	63	69	55	55	66
1400	53	1.22	47	33	49	69
1100	71	95	56	70	76	65
800	75	67	96	<u>1.08</u>	97	<u>1.26</u>

Temperature (degrees Celsius)

Indicators of accuracy of the mean of the gauge. J(%)

Pressure (bars)	-40	-33	-13	21	52	63
2300	45	81	58	83	50	56
2000	72	54	84	1.05	88	61
1700	92	57	76	66	69	68
1400	61	1.24	80	54	87	69
1100	1.00	1.47	70	95	81	1.09
800	1.28	1.43	1.08	1.23	92	1.24

Temperature (degree Celsius)

GAUGES: FAN
Indicators of precision of the gauge
F(%)

Pressure (bars)	-13	21	52	63
6500	1.85	30	21	26
6000	1.71	21	19	14
5200	1.24	49	18	20
4400	22	37	25	31
3700	49	31	32	26
2900	55	22	37	29
2200	44	28	40	17
1700	75	38	54	44

Temperature (degrees Celsius)

Indicators of accuracy of the mean of the gauge. J(%)

Pressure (bars)	-13	21	52	63
6500	<u>2.99</u>	84	1.61	1.15
6000	<u>2.02</u>	47	66	23
5200	1.20	67	1.26	<u>2.01</u>
4400	76	97	80	95
3700	1.01	43	50	49
2900	83	97	48	43
2200	72	91	69	1.12
1700	79	75	1.24	1.63

Temperature (degrees Celsius)

Notes:
(1) Values underlined are those that exceed the standard criteria.
(2) Panel IV (SP/2) may authorise 4% for F for pressures above 4000 bars at temperatures below -30C°.

CHAPTER 2

CHARACTERISTICS OF EACH APPROVED TYPE

1. All approved crusher gauges must be described by the appropriate nation in accordance with the following guidelines.

2. Their characteristics are to be summarised in Annex of Chapter 1 and are also to be included in a NATO document, together with:

2.1 Manufacturing nation, designation and date of approval.

2.2 Specifications and a set of fully dimensioned manufacturing drawings, including assemblies where necessary, an overall drawing and a components list. It is important that the parallelism tolerance between the piston and anvil faces when assembled should be specified on the appropriate drawing and that the drawings of the anvil and piston guide should specify the required hardness values.

2.3 Designation, form, dimensions and heat treatment (if required) of the crushers used.

2.4 Method of calibrating crusher gauges or crushers.

2.5 Description of firing tests carried out in accordance with Part IV of this publication; date and place of the firing and a complete report of the firings and test results.

2.6 Pressure and temperature ranges for which the crusher gauge is approved.

2.7 Temperature and pressure tarage tables.

PART II

INSTRUCTIONS FOR USE OF CRUSHER GAUGES

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1. Preparation

It should be noted that a crusher gauge is, by design, a precision instrument and should be handled as such. Crusher gauges should be assembled in a clean room with a dust-free atmosphere, as foreign matter inside crusher gauges may cause deterioration or actual damage leading to obturation failures. New crusher gauges should be lightly coated with a suitable grease. After dismantling, all gauge components, in particular the piston and bore (piston guide), should be carefully cleaned. The piston should be handled only with clean suitable tools to avoid any contamination.

2. Dimensional checks

Components shall be measured in accordance with their respective specifications and manufacturing drawings. This procedure shall be fully described in the specification. Measurements must include piston and bore diameter and the parallelism between piston and anvil faces and must be within the specified tolerances.

3. Assembly

Crusher gauges shall be assembled in accordance with national instructions.

4. Dismantling and measurement

After use in firings the crusher gauge shall be carefuly dismantled and the remaining length of the crusher shall be measured in multiples of 10 microns or less with an instrument having a resolution better than 5 microns so that measurement error does not exceed 10 microns. The pressure shall then be read from the tarage table obtained in accordance with Part IV, Chapter 4, of this publication, at the crusher gauge firing temperature.

NOTE: The values in the tarage table apply only to the crusher lot used in the acceptance tests conducted in accordance with Part IV of this publication.

PART III

CRUSHER SPECIFICATIONS

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1. Material

The purity of the raw material used for the crushers shall be specified and checked before manufacture.

2. Heat treatment

If a material requiring heat treatment is used for the crusher then the procedure shall be precisely specified and rigidly followed to minimise differences in crusher hardness.

3. Dimensional check

All dimensions must be within the specified tolerances.

Crushers shall be selected by national quality control methods. These methods must be submitted to Panel IV (Sub-Panel 2) for approval after examination by the Working Group of Experts (WGE.1).

4. Checking of batch homogeneity

The remaining length of a compressed crusher depends essentially on the following parameters:

1. actual dimensions;
2. hardness (mechanical strength);
3. level of load applied;
4. speed of application of the load.

Under given load conditions, dimensional and hardness homogeneity determines the reproducibility of compressive deformation of a new lot and hence the repeatability and accuracy of pressure measurements by crusher gauges.

The main factors affecting crusher homogeneity are:

1. random and/or systematic changes in the crushers manufacturing process;
2. differences in heat treatment (if applicable) from one batch to another.

By carrying out tests it is possible to determine the influence of these factors on pressure measurements and to remedy these shortcomings.

These tests fall into two groups: static tests and dynamic tests.

Static and/or dynamic tests must be carried out to evaluate the within and between batch homogeneity of the crushers.

4.1 Static test

The purpose of the static test is to evaluate crusher homogeneity. The procedure to be followed in this test will depend on national experience and preference. These procedures must be submitted to Panel IV (Sub-Panel 2) for approval after examination by the Working Group of Experts (WGE.1).

Statistical processing of the remaining length data will enable batches to be classified and static calibration tables to be drawn up if required.

4.2 Dynamic test

Dynamic testing using either a laboratory generator or a weapon may be used to examine the homogeneity of the crushers and where appropriate draw up dynamic calibration tables.

It may be used to group batches into a single lot or if this is not possible then to regroup batches into several lots.

Dynamic testing enables a more realistic comparison of batches to be made than is the case with static tests where the mechanical properties of the material are not fully taken into account. It is desirable that several applied load levels and temperatures are used in order to obtain comparison data over the full operating range of crusher.

The load-time profile of the dynamic generator should simulate as closely as possible a real weapon firing.

Statistical processing of the remaining lengths observed can be used:

- for grouping of batches;
- for drawing up dynamic calibration tables.

Static and/or dynamic tests must be conducted in accordance with any relevant national procedures. These procedures must be presented in the dossier supplied by each nation before the comparative firing trial for NATO approval.

PART IV

PROCEDURE FOR SUBMISSION OF
CRUSHER GAUGES FOR NATO APPROVAL

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CHAPTER 1

ACCEPTANCE PROCEDURE AND CRITERIA

1.1 To cover the pressure range from 500 to 6,500 bars and the temperature range from -40°C to +63°C a number of different types of crusher gauge may be required or alternatively the same gauge components may be used with different crushers.

If more than one crusher gauge design is required to cover the range 500 to 6,500 bars then an overlap of at least 600 bars between adjacent pressure ranges is necessary.

1.2 A country submitting one or more crusher gauges or crushers for approval shall provide:

1.2.1 manufacturing drawings and specifications of the gauge components and its associated crusher for each type of crusher gauge;

1.2.2 documents describing the procedures for laboratory checking and static and dynamic testing of the crushers (paragraphs 3 and 4 of Part III of this publication);

1.2.3 the results of the dynamic firing tests carried out for approval of the crusher gauges (Chapter 3 of Part IV of this publication);

1.2.4 after a crusher gauge has been approved by NATO, the results relating to the new batches of crushers as required in Part V of this publication.

1.3 The data shall be presented in the form of an Annex to the report giving the results of the dynamic firing tests. The results shall be analysed in accordance with the method indicated in Chapter 4 of Part IV of this publication. Any deviation from the acceptance criteria shall be indicated. AC/225(Panel IV/Sub-Panel 2) shall examine the approval request and shall have the right to grant, in the case of minor deviations, concessions from the criteria laid down (F, J).

CHAPTER 2

DEFINITION OF TERMS RELATING TO QUALITY OF MEASUREMENTS

2.1 Certain terms are used in the discussion of these tests and in the analysis of the test results. It is important that the definitions of these terms be clearly understood. They are as follows:

2.2 "The true pressure" is that value of maximum gas pressure which actually exists and would be measured by an ideal system. For present purposes, modern electrical sensors which record pressure as a function of time are considered to give the best possible estimation of "true pressure".

2.3 The "accuracy of the mean" of a pressure gauge is its ability to record or measure the "true pressure" without systematic error. It may depend on pressure level, temperature or both. Any systematic error due to the electrical gauges will result in an indeterminate error in the crusher pressures indicated in the tarage table.

2.4 The "precision" of a measuring instrument is its ability to give, under specified conditions of use, very similar readings on repeated application of a single input value at indeterminate time intervals. It indicates both the regularity and stability of the result given by a gauge and also the uniformity of data supplied by several gauges of the same type. In this case it is referred to as reproducibility.

2.5 The "reliability" of a sensor is a good indicator of its quality. During testing, it is determined by taking the ratio of the number of correct measurements supplied by the gauge to the number of measurements planned.

CHAPTER 3

DYNAMIC FIRING TESTS OF CRUSHER GAUGES

3.1 A crusher gauge submitted for NATO approval must have first undergone the dynamic firing tests described below. The following information shall be recorded during these tests: guns and ammunition used; time and place of firing; detailed description of the pressure time measurement system; the pressure time curves showing the absence of unacceptable pressure waves or ignition irregularities which might influence crusher gauge response; full details of all the remaining lengths and "true pressures" measured; the examination and analysis of the results in accordance with this Annex, for establishment of the tarage tables for pressure and temperature, as well as results for accuracy of mean, precision and reliability.

Every effort must be made to ensure that the crusher gauges do not move during firing. If crusher gauges move within or beyond the chamber, their recovered positions shall be recorded after the firing.

3.2 Two electrical pressure measuring systems, operating independently of one another and if possible using gauges based on different physical principles, shall be used to record chamber pressure-time history. The measuring systems shall have a frequency response from DC to 20kHz at at least 3dB. The gauges shall be located in the chamber in such a way that their expected signals are highly comparable, i.e. at the same distance from the breech face. If the difference between the two maximum pressure readings for a single round does not exceed 2% of their mean, this mean value shall be taken as the "true pressure". Otherwise, the data from the round shall be discounted and the round repeated.

3.3 It is essential that the crusher gauges and electrical gauges are located within the same section of the chamber in order to minimise error due to pressure gradient. The crusher gauges shall be orientated with their sensitive ends facing the muzzle and their sensitive axes parallel to the gun axis. The sensitive ends of the crusher gauges shall be located to within $\pm$25 mm of the plane containing the sensitive faces or axes (depending on orientation) of the electrical gauges.

3.4 To provide basic data for production of the tarage table, each crusher gauge shall be subjected to firings over a measurement range compatible with its design table.

All remaining lengths shall be measured with an instrument with such characteristics and resolution as to ensure a maximum uncertainty not exceeding ± 5 microns.

The pressure levels shall be at approximately 300 bar intervals up to 2,300 bars (LP crusher gauges) and approximately 700 bar intervals above 2,300 bars (HP crusher gauges). There shall be at least seven levels in the low pressure range and at least eight in the high pressure range.

If it proves necessary to conduct tests on a single crusher gauge in two different weapons, the pressure ranges covered by the weapons shall overlap by at least two pressure levels. The pressure limits may be adjusted according to circumstances subject to the agreement of Panel IV (Sub-Panel 2).

If a third type of crusher gauge is submitted by a single country the pressure ranges and levels for the test shall be decided by Panel IV (Sub-Panel 2).

3.5 As discussed in paragraph 3.2 of Part IV of this publication at least two electrical gauges shall be used for each firing. However if the weapon system is expected to produce large pressure gradients and if the crusher gauges cannot be prevented from moving during the firing then consideration should be given to installing a third electrical gauge within the chamber. The location of the third electrical gauge and the allowances to be made for pressure gradient shall be submitted to Panel IV (Sub-Panel 2) through the Working Group of Experts (WGE.1) for approval prior to the test.

Crusher gauges shall be used in groups of 5 for each type fired in the round, so for a weapon system that can accommodate a total of 15 gauges 3 different types may be fired per round.

For each pressure/temperature parameter pair, the number of firings carried out shall be such that 15 measurements are available for each type.

If 15 crusher gauges cannot be installed in the chamber of the weapon used (for reasons of space), the problem shall be re-examined by the Working Group of Experts (WGE.1) and recommendations submitted to Panel IV (Sub-Panel 2) for approval.

3.6 Each day's firing shall begin with a freshly calibrated set of electrical gauges. The gauges shall be recalibrated after a maximum of 20 rounds fired. Calibration shall be carried out on a test bench in accordance with the organizing country's method and if possible in the adaptors used for the firings.

The calibration relationship for the electrical gauge must be used in order to calculate pressure.

3.7 In order to produce a tarage table for pressure in terms of remaining length and temperature, firings shall be carried out with the crusher gauges conditioned at -40°C, -33°C, -13°C, +21°C, +52°C, +63°C and any other temperature decided by Panel IV (Sub-Panel 2). These temperatures must be maintained to within ±2°C after a conditioning time of 24 hours.

The tables shall be drawn at 50 micron intervals for the remaining length and at 5°C intervals for the temperatures, to which special values may be added, in particular the firing temperatures must be included.

CHAPTER 4

ANALYSIS OF RESULTS

4.1 General

It should be noted in the following analysis that although pressure is the independent variable for ease of analysis the remaining length has been taken as the independent variable. This is a reasonable assumption as the pressure generated by the gun leads to both piezo electric pressure and remaining length.

The statistical analysis described below assumes that there are at least two remaining length measurements available for each crusher gauge type after the firing (after elimination of defective measurements, e.g. resulting from gas leaks etc.). A firing for which only one value remains for a crusher gauge type shall be discounted for that crusher gauge type.

Each system shall be analysed separately.

4.2 Notation

Generic symbols

θ	temperature in °C;
P	pressure in bars;
L	remaining length of the crusher in microns;
g(L)	regression function: pressure as a function of remaining length at constant temperature;
$h'(\theta)$	regression function: pressure as a function of temperature at constant remaining length;
$h''(P)$	regression function: temperature as a function of pressure at constant remaining length;
α,β,γ	coefficients of function g;
u,v,w	coefficients of function h;

σ	regression standard deviation estimator;
n.d.f.	number of degrees of freedom of an estimator.

Indices and notation		Where first used
i	repetition test index for a given (θ,P) for the system being analysed	(1)
NI	number of repetition tests for the system under analysis for a given (θ,P)	(1)
t	experiment plan temperature index	(2)
NT	number of temperatures in the experiment plan	(2)
j	pressure level index number at each temperature in the experiment plan	(3)
NP	theoretical (i.e. planned) number of pressure levels per temperature in the experiment plan and per test	(3)
NP_{ti}	number of pressure levels attained for temperature θ_t, during test i	(6)
k	index number of the remaining length measurement at a point (θ,P) of the experiment plan, for test i	(5)
M	theoretical (i.e. planned) number of remaining length measurements at each planned point (θ,P) in the experiment plan per test	(5)
M'_{tij}	number of remaining length measurements made at a point achieved in the experiment plan (θ_t, P'_{tij}), after elimination of defective measurements, for test i	(7)

M''_{tij}	as above, after elimination of defective measurements and outliers, for test i	(15)
r	tarage table temperature index	(34)
NR	number of temperatures in the tarage table	(34)
s	tarage table remaining length index	(18)
NS	number of remaining lengths in the tarage table	(18)

Planned, achieved and measured values		Where first used
θ_t	value of the tth temperature in the experiment plan	(2)
P^*_j	value of the jth theoretical (i.e. planned) pressure in the experiment plan	(45)
P_{tij}	value of the jth pressure achieved for temperature θ_t, during test i ("true pressure")	(4)
P^P_{tij}	mean of the two values measured by the piezo-electric gauges, estimating the achieved pressure P_{tij}	(4)
σ'_{tij}	uncertainty on P_{tij} due to the accuracy of the measurements leading to P^P_{tij} (by piezo-electric gauges)	(12)
L_{tijk}	value of the kth remaining length measurement at point (θ_t, P_{tij}), from the kth crusher	(5)
$\bar{L}_{tij}$	corresponding mean value	(20)
θ_r	value of the rth temperature in the tarage table	(35)

L_s	value of the sth remaining length in the tarage table	(19)

Calculated and estimated values		Where first used
$\hat{P}_{tijk}$	pressure estimated by the regression function g(L) for the kth length measurement L_{tijk} at point (θ_t, P_{tij})	(10)
$\hat{P}^T_{tijk}$	pressure estimated by the tarage table for the kth length measurement L_{tijk} at point (θ_t, P_{tij})	
$\bar{P}^T_{tij}$	corresponding mean pressure at point (θ_t, P_{tij})	(38)
E'_{ti}	quadratic error to be minimised for regression from the available measurements (excluding defective measurements) at temperature θ_t, in test i	(11)
g'_{ti}	associated regression function	(8)
σ_{ti}	associated standard deviation of regression	(13)
E''_{ti}	quadratic error to be minimised for regression from the measurements selected (excluding defective measurements and outliers) at temperature θ_t, during test i	(17)
g''_{ti}	associated regression function	(17)
P^C_{tsi}	calculated pressure at each point (θ_t,L_s) for the temperatures θ_t in the experiment plan and the remaining lengths L_s in the tarage table, in test i	(19)
$\hat{P}_{tsi}$	corresponding estimated pressure at point (θ_t,L_s), in test i	(26)

γ^2_{tsi}	weighting coefficient for minimising of E'_{si} and E''_{si}	(23)
E'_{si}	quadratic error to be minimised for direct regression at length L_s, during test i	(27)
EN'_{si}	associated standardized quadratic error	(28)
h'_{si}	associated regression function	(24)
$\hat{\theta}_t$	estimator of θ_t during minimisation of E''_{si}	(31)
E''_{si}	quadratic error to be minimised for inverse regression at length L_s, in test i	(32)
EN''_{si}	associated standardized quadratic error	(33)
h''_{si}	associated regression function	(29)
P_{rsi}	calculated pressure at each point (θ_r,L_s) in the tarage table, in test i	(35)
$\bar{P}_{rs}$	corresponding mean pressure at point (θ_r,L_s)	(43)
$(\bar{P}_{rs})$	matrix of the values of $\bar{P}_{rs}$ constituting the tarage table for the system analysed	(44)

Performance indicators		Where first used
$J_i(\theta,P)$	gauge accuracy indicator value at a point (θ,P) in test i	(37)
$J(\theta,P)$	as above, for all tests	(49)
$F_i(\theta,P)$	gauge repeatability indicator value at a point (θ,P) in test i	(38)
$F(\theta,P)$	as above, for all tests	(50)

$Q_1(\theta,P)$ value of the first gauge quality indicator at a point (θ,P): reliability of the gauge as indicated by defective measurements alone (51)

$Q_2(\theta,P)$ value of the second gauge quality indicator at a point (θ,P): percentage of correct operation of the gauge, i.e. the reliability as indicated by all the values eliminated (after elimination of defective measurements and outliers (52)

$Q_3(\theta,P)$ value of the third gauge quality indicator at a point (θ,P): reliability as indicated by the outliers (53)

4.3 Analysis of the system under consideration

Analysis is in two stages:

- analysis for each test i in the system:

  $1 \leq i \leq NI$ (1)

- "global" analysis for all the NI tests.

4.3.1 Analysis of test number i of the system

4.3.1.1 Analysis per temperature θ_t in the experiment plan:

For each temperature θ_t, $1 \leq t \leq NT$ carry out operations 4.3.1.1.1 to 4.3.1.1.4 below: (2)

4.3.1.1.1 ~~Calibration of the regression~~ functions at temperature θ_t:

(a) Measurements carried out

For each firing at a pressure level j, $1 \leq j \leq NP$ (3)

- pressure measurements from the two piezo-electric gauges; the mean of the two values is an estimate of the "true pressure":

$$P_{tij} = P\ _{tij} \qquad (4)$$

- measurement of M remaining length values on the M crushers to be calibrated

$$L_{tijk},\ 1 \leq k \leq M \qquad (5)$$

(b) Data selected:

- as some pressures will be mission, only NP_{ti} firings at temperature θ_t will be available:

$$1 \leq j \leq NP_{ti} \leq NP \qquad (6)$$

- after elimination of the defective measurements, M'_{tij} remaining length values at point $(\theta_t, P^{\rho}_{tij})$ are selected:

$$1 \leq k \leq M'_{tij} \leq M \qquad (7)$$

(c) Adjustment by "exponential regression":

- regression model:

$P_{tij} - g'_{ti}(L_{tijk})$ + "residual error" where (8)

$$g'_{ti}(L) = \gamma'_{ti} + \beta'_{ti}.\exp\ (\alpha'\ _{ti}.L) \qquad (9)$$

or

$$\alpha'_{ti}.L + \beta'_{ti}\ (\gamma'_{ti}=0)$$

- associated estimation:

$$\hat{P}_{tijk} = g'_{ti} (L_{tijk}) \qquad (10)$$

- regression by minimizing, under the constraint $\alpha'_{ti} \leq 0$, the "quadratic error":

$$E'_{ti} = \sum_{j=1}^{N P_{ti}} \sum_{k=1}^{M'_{tij}} \left[\frac{\hat{P}_{tijk} - P^{\rho}_{tij}}{\sigma'_{tij}} \right]^2 \qquad (11)$$

where

$$\sigma'_{tij} = 1\%.P^{\rho}_{tij} \qquad (12)$$

is an estimate of the measurement error on the pressures supplied by the piezo-electric gauges, (minimisation is carried out in relation to parameters α'_{ti}, β'_{ti}, and γ'_{ti})

- exponential regression: use the estimates of P_{tijk} supplied by the exponential function g'_{ti}

- if

  $|\alpha'_{ti}| \leq 2.10^{-3}$

  linear regression: use the estimates corresponding to the linear form of g'_{ti} (with $\gamma'_{ti} = 0$)

- regression residual standard deviation:

$$\sigma_{ti} = (E'_{ti}\ (\text{minimum})/\text{n.d.f})^{1/2} \qquad (13)$$

where the number of degrees of freedom of the regression is given by:

$$\text{n.d.f.} = \left[\sum_{j=1}^{NP_{ti}} M'_{tij}\right] - 3 \qquad (14)$$

or

$$\text{n.d.f.} = \left[\sum_{j=1}^{NP_{ti}} M'_{tij}\right] - 2 \text{ for the linear case}$$

where the sum represents the total number of measurements carried out and not defective (for temperature θ_t).

4.3.1.1.2 Processing of outliers at temperature θ_t:

(a) Determination of outliers from the Tietjen-Moore method, in the following variant:

- double determination of the number of outliers by the "greatest deviation" and "second greatest deviation" procedure;

- determination of the outliers from the table corresponding to the type I risk 5%.

(b) Elimination of outliers:

- elimination of the values of measurements detected by the test in (a) above;

- after this elimination, we have M''_{tij} remaining length values at point $(\theta_t, P^{\rho}_{tij})$:

$$1 \leq k \leq M''_{tij} \leq M'_{tij} \leq M \qquad (15)$$

(c) Coherency of the two high pressure regression functions in the overlap region:

- perform a linear regression on the M''_{tij} measurements in the overlap region $(\theta_t, P^{\rho}_{tij})$ corresponding to the first weapon, then a similar linear regression for the second weapon;

- estimate the quality of the overlap by comparing the two regression straight lines from the t tests giving the corresponding type I risk.

4.3.1.1.3 ~~Corrected regression functions at temperature~~ θ_t:

(a) Available data:

- for the NP_{ti} firing at temperature θ_t (4.3.1.1.1.b);

- after elimination of outliers (4.3.1.1.2.b);

- we have M''_{tij} remaining length values at each point $(\theta_t, P^{\rho}_{tij})$.

(b) If outliers have been eliminated, i.e. if:

$$\sum_{j=1}^{NP_{ti}} M''_{tij} < \sum_{j=1}^{NP_{ti}} M'_{tij} \qquad (16)$$

(the number of valid measurements at temperature θ_t has diminished), perform the regression stage in c. below; otherwise keep function g''_{ti} identical to g'_{ti}

(i.e. $\alpha''_{ti} = \alpha'_{ti}$, $\beta''_{ti} = \beta'_{ti}$, $\gamma''_{ti} = \gamma'_{ti}$), and move on to 4.3.1.1.4.

(c) Adjustment by exponential regression:

Use the model in 4.3.1.1.1.c with M''_{tij} measurements at (θ_t, P_{tij}) instead of M'_{tij}, giving a function:

$$g''_{ti}(L) = \gamma''_{ti} + \beta''_{ti} \cdot \exp(\alpha''_{ti} \cdot L) \qquad (17)$$

or

$$\alpha''_{ti} \cdot L + \beta''_{ti} \quad (\gamma''_{ti} = 0)$$

obtaining by minimising E''_{ti} with $|\alpha''_{ti}| \leq 2.10^{-3}$

4.3.1.1.4 Discretisation of the curves $P = g''_{ti}(L)$:

Calculation of the pressure for each length in the tarage table:

for $1 \leq s \leq NS$ (18)

perform $P^c_{tsi} = g''_{ti}(L_s)$ (19)

4.3.1.2 Correction of each length L_s in the tarage table for temperature:

For each length L_s, $1 \leq s \leq NS$

Perform operations 4.3.1.2.1 to 4.3.1.2.3 below.

4.3.1.2.1 Regression functions at length L_s:

(a) Available data:

- for the NT temperatures θ_t in the experiment plan;

- the pressures P^c_{tsi} interpolated from the exponential curves;

- $P = g''_{ti}(L)$(cf. 4.3.1.1.4);

- the M''_{tij} lengths L_{tijk} for $j = j', j''$ such that the mean lengths $\bar{L}_{tij'}$ and $\bar{L}_{tij''}$ bracket L_s:

$$\bar{L}_{tij'} \leq L_s \leq \bar{L}_{tij''} \qquad (20)$$

(see calculation of mean lengths in (b) below).

(b) Calculation of weighting coefficients:

- for $j = j', j''$, calculation of the standardized variance

$$V^2_{tij} = \frac{1}{M''_{tij} - 1} \sum_{k=1}^{M''_{tij}} \left[\frac{L_{tijk} - \bar{L}_{tij}}{\bar{L}_{tij}} \right]^2 \qquad (21)$$

in which mean length is given by

$$\bar{L}_{tij} = \frac{1}{M''_{tij}} \sum_{k=1}^{M''_{tij}} L_{tijk} \qquad (22)$$

any zero values of V^2_{tij} will be replaced by the value of the V^2_{tij} corresponding to the resolution of the measurement tools used at the time of the NATO comparative trial;

- linear interpolation in L (or in P) between j' and j'': e.g.:

$$V^2_{tsi} = V^2_{tij'} + (V^2_{tij''} - V^2_{tij'}) \frac{L_s - \bar{L}_{tij'}}{\bar{L}_{tij''} - \bar{L}_{tij'}} \quad (23)$$

any zero values of V^2_{tsi} will be replaced by the value of the V^2_{tsi} corresponding to the resolution of the measurement tools used at the time of the NATO comparative trails.

(c) Adjustment of parabolic regression:

Case 1:

- direct regression model:

$$P_{tsi} = h'_{si}(\theta_t) + \text{"residual error"} \quad (24)$$

where

$$h'_{si}(\theta) = u'_{si} + V'_{si}.\theta + w'_{si}.\theta^2 \quad (25)$$

- associated estimation

$$\hat{P}_{tsi} = h'_{si}(\theta_t) \quad (26)$$

- regression by minimising the quadratic error:

$$E'_{si} = \sum_{t=1}^{NT} \frac{(\hat{P}_{tsi} - P^c_{tsi})^2}{V^2_{tsi}} \quad (27)$$

under constraint of monotony and convexity: for any θ, $w'_{si} \geq 0$

$$Dh'_{si}(\theta) = v'_{si} + 2w'_{si}.\theta \leq 0$$

(D = derivative)

(minimisation is carried out in relation to parameters u'_{si}, v'_{si}, w'_{si})

- calculation of the standardized quadratic error:

$$EN'_{si} = \sum_{t=1}^{NT} \left[\frac{\hat{P}_{tsi} - P^c_{tsi}}{P^c_{tsi}} \right]^2 \qquad (28)$$

Case 2:

- inverse regression model

$$\theta_t = h''_{si}\,(P^c_{tsi}) + \text{"residual error"} \qquad (29)$$

where

$$h''_{si}(P) = u''_{si} + v''_{si}.P + w''_{si}.P^2 \qquad (30)$$

- associated estimation:

$$\hat{\theta}_t = h''_{si}(P^c_{tsi}) \qquad (31)$$

- regression by minimisation of the quadratic error:

$$E''_{si} = \sum_{t=1}^{NT} \left[\frac{(\hat{\theta}_t - \theta_t)^2}{V^2_{tsi}} \right] \qquad (32)$$

under constraint of monotony and convexity: for any P, $w''_{si} \geq 0$

$Dh''_{si}(P) = v''_{si} + 2\,w''_{si}.P \leq 0$

(D = derivative)

(minimisation is carried out in relation to parameters u''_{si}, v''_{si}, w''_{si})

- calculation of the standardized quadratic error:

$$EN''_{si} = \sum_{t=1}^{NT} \left[\frac{\hat{\theta}_t - \theta_t}{\theta_t} \right]^2 \qquad (33)$$

Choice of the model

- by comparison of the standardized errors:

- if $EN'_{si} \leq EN''_{si}$, select case 1; otherwise select case 2.

4.3.1.2.2 Construction of tarage table for test i

Calculation of the pressure for each temperature in the tarage table:

for $1 \leq r \leq NR$ (34)

if case 1 has been selected:

perform $P_{rsi} = h'_{si}(\theta_r)$ (35)

otherwise (i.e. if case 2 has been selected) solve equation $h''(P_{rsi}) = \theta_r$ (36)

(P_{rsi} is the smallest root).

4.3.1.2.3 Performance of the crusher gauge for test i

(a) Definition of the performance criteria associated with the accuracy of the crusher gauge:

- performance indicators of the gauge's accuracy of the mean

at a point (θ_t, P_{tij}) in the plan

$$J_i(\theta_t, P^\rho_{tij}) = \left[\frac{1}{M''_{tij}} \sum_{k=1}^{M''_{tij}} \left[\frac{\hat{P}^T_{tijk} - P^\rho_{tij}}{P^\rho_{tij}} \right]^2 \right]^{1/2} . 100\% \quad (37)$$

where $\hat{P}^T_{tijk}$) is the kth pressure estimated from the kth length L_{tijk} at this point, calculated by linear interpolation from the tarage table (P_{rsi}) (cf. (b) below);

- crusher gauge repeatability performance indicators: with the same notation,

$$F_i(\theta_t, P^\rho_{tij}) = \left[\frac{1}{M''_{tij} - 1} \sum_{k=1}^{M''_{tij}} \left[\frac{\hat{P}^T_{tijk} - \bar{P}^T_{tij}}{\bar{P}^T_{tij}} \right]^2 \right]^{1/2} . 100\% \quad (38)$$

where $\bar{P}^T_{tij}$ is the mean pressure estimated by means of the tarage table, at point (θ_t, P^ρ_{tij}) (cf. b.).

(b) Calculation of estimated pressure at point (θ_t, P^ρ_{tij}):

- finding of the temperature index r from the tarage table such that

$\theta_r = \theta_t$ (of the point under consideration) (39)

- bracketing of each length L_{tijk}, for $1 \leq k \leq M''_{tij}$, by tarage lengths L_s' and L_s'':

$$L_s' \leq L_{tijk} \leq L_s'' \quad (40)$$

- calculation of each estimated pressure $\hat{P}^T_{tijk}$ $(1 \leq k \leq M''_{tij})$ by linear interpolation from the pressures in the tarage table:

$$\hat{P}^T_{tijk} = P_{rs'i} + (P_{rs''i} - P_{rs'i}) \frac{L_{tijk} - L_{s'}}{L_{s''} - L_{s'}} \quad (41),$$

- calculation of the corresponding mean pressure:

$$\bar{P}^T_{tij} = \frac{1}{M''_{tij}} \sum_{k=1}^{M''_{tij}} \hat{P}^T_{tijk} \quad (42)$$

4.3.2 Analysis of all the tests of the system

4.3.2.1 Calculation of the tarage table for the system analysed:

From the NI tarage tables (P_{rsi}) for each test i, average the estimated pressure values:

for $1 \leq r \leq NR$, $1 \leq s \leq NS$

calculate

$$\bar{P}_{rs} = \frac{1}{NI} \sum_{i=1}^{NI} P_{rsi} \qquad (43)$$

which gives the definitive tarage table

$$(\bar{P}_{rs})\ 1 \leq r \leq NR,\ 1 \leq s \leq NS \qquad (44)$$

4.3.2.2 Crusher gauge performance (for all tests):

4.3.2.2.1 Performance criteria associated with the accuracy of the crusher gauge:

(a) Available values:

- the temperature in the plan:

  (θ_t), $1 \leq t \leq NT$

- the planned pressures:

  (P^*_j), $1 \leq j \leq NP$ (45)

- the pressures achieved during each test i:

  (P^p_{tij}), $1 \leq t \leq NT$, $1 \leq j \leq NP_{ti}$, $1 \leq i \leq NI$

- the corresponding performance indicators:

  $J_i(\theta_t, P^p_{tij})$ and $F_i(\theta_t, P^p_{tij})$

(b) Pressure standardization:

- for each test i, $1 \leq i \leq NI$, for each temperature θ_t, $1 \leq t \leq NT$;

- calculate $J_i(\theta_t, P^*_j)$ and $F_i(\theta_t, P^*_j)$ by linear interpolation, for $1 \leq j \leq NP$:

$$J_i(\theta_t,P^*_j) = J_i(\theta_t,P^\rho_{tij'}) + (J_i(\theta_t,P^\rho_{tij''})-J_i(\theta_t,P^\rho_{tij'}))\times \left[\frac{P^*_j - P^\rho_{tij'}}{P^\rho_{tij''} - P^\rho_{tij'}}\right] \quad (46)$$

$$F_i(\theta_t,P^*_j) = F_i(\theta_t,P^\rho_{tij'}) + (F_i(\theta_t,P^\rho_{tij''}) - F_i(\theta_t,P^\rho_{tij'})) \times \left[\frac{P^*_j - P^\rho_{tij'}}{P^\rho_{tij'} - P^\rho_{tij'}}\right] \quad (47)$$

where j' and j'' are indexed such that $P^\rho_{tij'}$ and $P^\rho_{tij''}$ bracket P^*_j:

$$P^\rho_{tij'} \leq P^*_j \leq P^\rho_{tij''} \quad (48)$$

(c) Performance indicators for all tests:

- mean squared J_i:

for $1 \leq t \leq NT$, $1 \leq j \leq NP$

$$\text{calculate } J(\theta_t, P^*_j) = \left[\frac{1}{NI}\sum_{i=1}^{NI} J_i^2(\theta_t,P^*_j)\right]^{1/2} \quad (49)$$

in general J must not exceed 2%, except that for pressures above 4000 bars occurring at temperatures below -30°C when J must not exceed 4%;

- mean square F_i:

  for $1 \leq t \leq NT$, $1 \leq j \leq NP$

  calculate

$$F(\theta_t, P^*_j) = \left[\frac{1}{NI} \sum_{i=1}^{NI} (F_i(\theta_t, P^*_j))^2 \right]^{1/2} \qquad (50)$$

  in general F must not exceed 1%, except that for pressures above 4000 bars or at temperatures below -30°C when F must not exceed 2%; 4% may be allowed by Panel IV (Sub-Panel 2) for pressures above 4000 bars occurring at temperatures below -30°C.

4.3.2.2.2 Crusher gauge quality performance criteria:

(a) Available values:

- the temperatures in the plan:

  (θ_t), $1 \leq t \leq NT$

- the planned pressures:

  (P^*_j), $1 \leq j \leq NP$

- the numbers of remaining length measurements at each point (θ_t, P^P_{tij}), in each test i:

  M'_{tij} and M''_{tij}, $1 \leq t \leq NT$, $1 \leq j \leq NP_{ti}$, $1 \leq i \leq NI$

(b) Definition and calculation of crusher gauge quality indicators:

- reliability as indicated by defective measurements alone:

$$Q_1(\theta_t, P^*_j) = \sum_{i=1}^{NI} M'_{tij}/(NI.M) \qquad (51)$$

- reliability as indicated by defective measurements and outliers:

$$Q_2(\theta_t, P^*_j) = \sum_{i=1}^{NI} M''_{tij}/(NI.M) \qquad (52)$$

- reliability as indicated by outliers alone:

$$Q_3(\theta_t, P^*_j) = \left[\sum_{i=1}^{NI} M''_{tij}\right] \Big/ \left[\sum_{i=1}^{NI} M'_{tij}\right] \qquad (53)$$

4.3.2.3 Use of the tarage table for the system analysed:

From a measured pair (θ, L), the pressure P is estimated by double linear interpolation (length, then temperature), as follows:

- finding of the indices r' and r'' (between 1 and NR) such that:

$$\theta_{r'} \leq \theta \leq \theta_{r''} \qquad (54)$$

- finding of the indices s' and s'' (between 1 and NS) such that:

$$L_{s'} \leq L \leq L_{s''} \qquad (55)$$

- the pair (θ, L) has been bracketed by a quadrilateral of apices $(\theta_{r'}, L_{s'})$,

  $(\theta_{r'}, L_{s''})$, $(\theta_{r''}, L_{s'})$, $(\theta_{r''}, L_{s''})$:

  we therefore know the 4 pressures from the tarage table corresponding to the apices, i.e. $\bar{P}_{r's'}, \bar{P}_{r's''}, \bar{P}_{r''s'}, \bar{P}_{r''s''}$

- linear interpolation in L at temperature $\theta_{r'}$:

$$P_{r'L} = \bar{P}_{r's'} + (\bar{P}_{r's''} - \bar{P}_{r's'}) \frac{L - L_{s'}}{L_{s''} - L_{s'}} \qquad (56)$$

- linear interpolation in L at temperature $\theta_{r''}$:

$$P_{r''L} = \bar{P}_{r''s'} + (\bar{P}_{r''s''} - \bar{P}_{r''s'})\frac{L - L_{s'}}{L_{s''} - L_{s'}} \quad (57)$$

- linear interpolation in θ at length L:

$$P_{\theta L} = P_{r'L} + (P_{r''L} - P_{r'L})\frac{\theta - \theta_{r'}}{\theta_{r''} - \theta_{r'}} \quad (58)$$

The estimated value of the unknown pressure P is taken to be the value $P_{\theta L}$ thus calculated.

PART V

APPROVAL OF CRUSHER GAUGES

AEP-23

09/91

1. The comparative tests defined in Part IV of this publication for submission of crusher gauges for approval shall be carried out in accordance with this publication at approximately five-year intervals, on a date and in a place determined by AC/225(Panel IV/Sub-Panel 2).

   The firing tests shall not be carried out twice in succession in one country.

2. Any country must notify Panel IV (Sub-Panel 2) of its intention to submit a crusher gauge for NATO approval. If it intends to carry out its own firings (in accordance with Part IV of this publication), the firings must be carried out in conjunction with another crusher gauge already approved. The Panel shall take the necessary steps to ensure that another country supplies enough crusher gauges of a previously approved type for use during the firings.

3. If, following approval of a crusher gauge by NATO, a new lot of crushers is to be brought into service, the new lot must be compared with the previously approved lot by an appropriate dynamic test method.

   The method, the results of these tests and the tests described in Part III of this publication shall be submitted to Panel IV (Sub-Panel 2) for approval.